Guide, Focus/Alignment System for BigBOSS

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ABSTRACT

The BigBOSS experiment is a proposed DOE-NSF Stage IV dark energy survey. The all sky survey will be used to study the baryon acoustic oscillation (BAO) and growth of large scale structure from $0.2 < z < 3.5$. Key to the timely success of BigBOSS is the total optical throughput of the system. The guide, focus/alignment system will provide essential pointing information, field acquisition, atmospheric monitoring and alignment corrections all used to maximize light throughput.

Keywords: BigBOSS, telescope guiding, focus/alignment, BAO

1. INTRODUCTION

BigBOSS is a proposed DOE-NSF Stage IV ground-based dark energy experiment[1]. The experiment will measure the baryon acoustic oscillation (BAO) effect by creating an all sky galaxy red shift map. The survey will provide 14,000 square degrees with galaxy redshifts between $0.2 \leq z \leq 1.7$. Additionally, the Lyman alpha (L-α) forest from QSOs will map the structure of matter between $1.9 \leq z \leq 3.4$.

BigBOSS is a multi-object spectrograph built up from 5000 robotically actuated optical fibers. BigBOSS will be installed on the NOAO four meter Mayall telescope located at Kitt Peak near Tucson, Arizona. The optical system will provide a three degree diameter field of view. The fibers will feed several three arm spectrographs covering wavelengths from 360 nm $\leq \lambda \leq$ 980 nm.

The survey will map over 20,000,000 galaxies using 500 dark/gray nights spread over 5 years.

2. GUIDE, FOCUS/ALIGNMENT SYSTEM

The success of BigBOSS depends heavily on the total optical throughput of the system. Factors affecting throughput include source brightness, sky background, optical transmission, fiber throughput and the focus and alignment of the galaxy light on the fiber tips. The final term is the responsibility of the guide, focus/alignment system.

First, the system acquires the current pointing of the telescope and using guide signals to the telescope control system (TCS) provides an initial alignment of the sources on the arranged fiber tips. Once initially aligned, the system provides 1 Hz guide signals to maintain proper pointing. Finally, by measuring the wavefront throughout each exposure, focus and alignment of the system are provided by updates to the hexapod system.

For measuring focus and alignment of the system, each guide location also has one intra and one extra-focal sensor. By measuring changes in the wavefront using defocussed stars. corrections in focus, tip and tilt can be provided to the hexapod between exposures. Details of the focus and alignment algorithms is not discussed here but can be found in references [2].

BigBOSS is in the initial design stages and a baseline design for the guide, focus and alignment system is provided.

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Table 1. Sensors evaluated for use in the BigBOSS guide, focus/alignment system.

Manufacturer Model	Area† [cm²]	Dark Current at 25 C [e⁻/pixel s]	Read Noise [σ_{e-}]	Nom. Rate [MHz]	Pixels H x V†	Pixel Size [μm]	Notes
Kodak KAF09000	13.4	5	7	3	3056 x 3056	12	1 channel
Kodak KAF3200E	1.5	20	7	1	2148 x 1510	6.8	Small
e2v ccd230-42	9.4	20	8.5	1	2048 x 2064	15	
e2v ccd230-84	37.7	20	8.5	1	4096 x 4112	15	Large
Kodak KAF1602E	1.2	50	15	10	1538 x 1024	9	Small
Kodak KAF6303	5.1	50	15	4	3072 x 2048	9	1 channel
Kodak KAF16801E	13.6	50	15	2	4096 x 4096	9	1 channel
Fairchild ccd3041	9.4	209	6.5	1	2048 x 2048	15	Dark
Kodak KAF1301E	3.4	238	15	1	1280 x 1024	16	Dark
e2v ccd47-10	1.9	274	6	1	1056 x 1027	13	Small
Atmel TH7899M	8.2	304	5	1	2048 x 2048	14	Dark
e2v ccd30-11 OE	1.8	503	12	1	1024 x 256	26	Dark/Small
e2v ccd42-40	7.6	501	8	1	2048 x 2048	13.5	Dark
Kodak KAF1001E	6.0	550	13	1	1024 x 1024	24	Dark
e2v ccd77-00	0.4	703	6.5	1	512 x 512	24	Dark/Small
Kodak KAF0261E	1.0	744	22	1	512 x 512	20	Dark/Small
Kodak KAF1001E	6.0	1071	13	1	1024 x 1024	24	Dark
Sony ICX205AL	0.3	?	3	1	1360 x 1024	4.65	Small
Sony ICX285AL	0.6	?	3	1	1360 x 1024	6.45	Small
Canon EOS20D	3.4	3-30 [3]	≤ 10	ISO400	3504 x 2336	6.5	Atypical use
DALSA/Teledyne H2RG HyVisi	13.6	5-10	4	4096 x 4096	18		cryo only [4]
BAE CIS2051 sCMOS	2.33	≤ 20 [5]	1.9	30 fps	2560x2160	6.5	
† Only 50% of (vertical) area used in frame transfer mode							

2.1 Sensor Selection

Table 1 shows several of the sensors evaluated for use in the BigBOSS guide, focus and alignment system. Key parameters considered include active area, dark current at ambient temperature, read noise and pixel size. The notes column provides indication why the sensor was not selected.

Sensors were down selected based on their overall signal to noise (SNR). As the SNR increases the minimum brightness for the guide star also increases. As fainter stars are more abundant, the required total surface area of sensors decreases with improved SNR. Available star counts vs galactic declination and SNR are discussed in Sections 3 and 4 respectively. The requirement to operate at ambient temperature limits the sensor selection to back illuminated sensors operating in inverted mode. Several Kodak sensors met the read noise and dark current requirements but all operated in single channel full frame mode. The e2v ccd230-42 was selected for use in the baseline design.

The guide, focus/alignment system is comprised of three sensor units mounted at the edge of the BigBOSS optical field with 120 degree spacing. The sensor used in all baseline designs is the E2V ccd230-42, a 2K by 2K back illuminated ccd operating in advanced inverted mode operation (AIMO). The sensor was selected for it large area, 4 channel readout in split frame transfer mode and relatively low dark current at ambient temperatures (via AIMO). Most sensors evaluated were back illuminated charged coupled devices (CCDs). However, several manufacturers also offer both commercial and scientific CMOS sensors with low dark current and large area. Extensive work has been done on the DALSA/Teledyne H2RG HyVisi[4] and the sCMOS devices from Fairchild look particularily promising. In order to prototype the design, the e2v ccd230-42 was selected due to its excellent performance and significant industry experience with the device.

2.2 Optical Filter

An optical filter will enclose the sensors. Since red stars are the most abundant (see Section 3) an R-band filter will be used. A trade is required to balance counts, the width of the filter transmission band, sky noise and increasing lateral color distribution at longer wavelengths. For in focus stars, spot size is dominated by seeing. However, for the out of focus stars in the wave guide sensors and the lateral profile versus color has an increasing effect. A 100 nm FWHM optical filter centered at $\lambda = 650$ nm is proposed.

2.3 Shutter

The guide, focus/alignment system is designed to operate without a shutter. However, since the sensor temperature varies with ambient temperature the ability to measure dark current throughout the night may prove to be required. Typically, one can use the overscan channels of the sensor or the frame store region itself to measure the dark current. However, until the sensors have been acquired and parameterized a shutter is being included in the design for risk mitigation.

Bonn Shutter UG is a professional shutter development company that was created from the instrumentation group at the Argelander Institute for Astronomy. They have developed large format astronomy shutters for dozens of astronomy projects including DECam, PanSTARRS and OmegaCam. While the shutters needed for BigBOSS are atypically small, they quickly developed an affordable, single blade shutter for the guide, focus/alignment system. The shutter can open/close within one second, has less than 400 grams of components and fits within the desired footprint. The shutter uses 36V DC power and leverages the well developed Bonn Shutter controller.

3. STAR COUNTS

In order to meet the required guide requirements, several stars of sufficient brightness are needed. The availability of stars decreases with distance from the galactic plane. Bahcall and Soneria have modelled star count vs magnitude and galactic latitude[6, 7]. The required minimum brightness of the guide star depends on several sensor parameters and is described in section 4. With the selected sensor, we are requiring a total of 10 guide stars be available within the magnitude range of $15.0 < R < 17.0$. This represents a factor of 2.5 in signal strength making maximal use of the sensor dynamic range. Using the NOMAD star catalog Figure 1 shows that near the north galactic pole (NGP) within the required magnitude range there are around 450-500 stars per square degree. This corresponds to an average of 2.3 stars per sensor (operating in frame transfer mode). Reference [6] predicts 458 stars with $R \leq 16.75$ at NGP.

Figure 2 shows the approximate footprint of the BigBOSS survey. To determine the best configuration of sensors, 100,000 random pointings over this region and the number of guide stars for several sensor configurations was determined. Table 2 lists the percentage of fields that had at least 10 stars, the percentage of fields where every guide, focus/alignment unit had at least one guide star and the percentage of fields where both of those conditions were true. Configurations with one versus two guide sensors per unit and configurations where BigBOSS had three versus four guide, focus/alignment units. Additionally, Table 2 compares these configurations for fields above 20° galactic latitudes.

It is clearly preferable to have two guide sensors per unit. With two guide sensors per unit, a total of ten guide stars (and at least one per unit) is achieved for at least 97% of the BigBOSS survey. However, in the star poor region above |b| > 70° only 81% of fields meet a "10 guide star" specification in a 3 unit configuration. With 4 guide units, 95% of fields above |b| > 70° still achieve a the 10 guide specification.

In all configurations there remain occurrences where the desired minimum number of guide stars is not available. These cases can be mitigated by increasing the integration time on the guide sensors and slowing the telescope guide rate. Additionally, slightly altering a pointing to obtain better guiding could be done. An example, would be to shift the entire pointing by an angle equivalent to the spacing between fiber positioners.
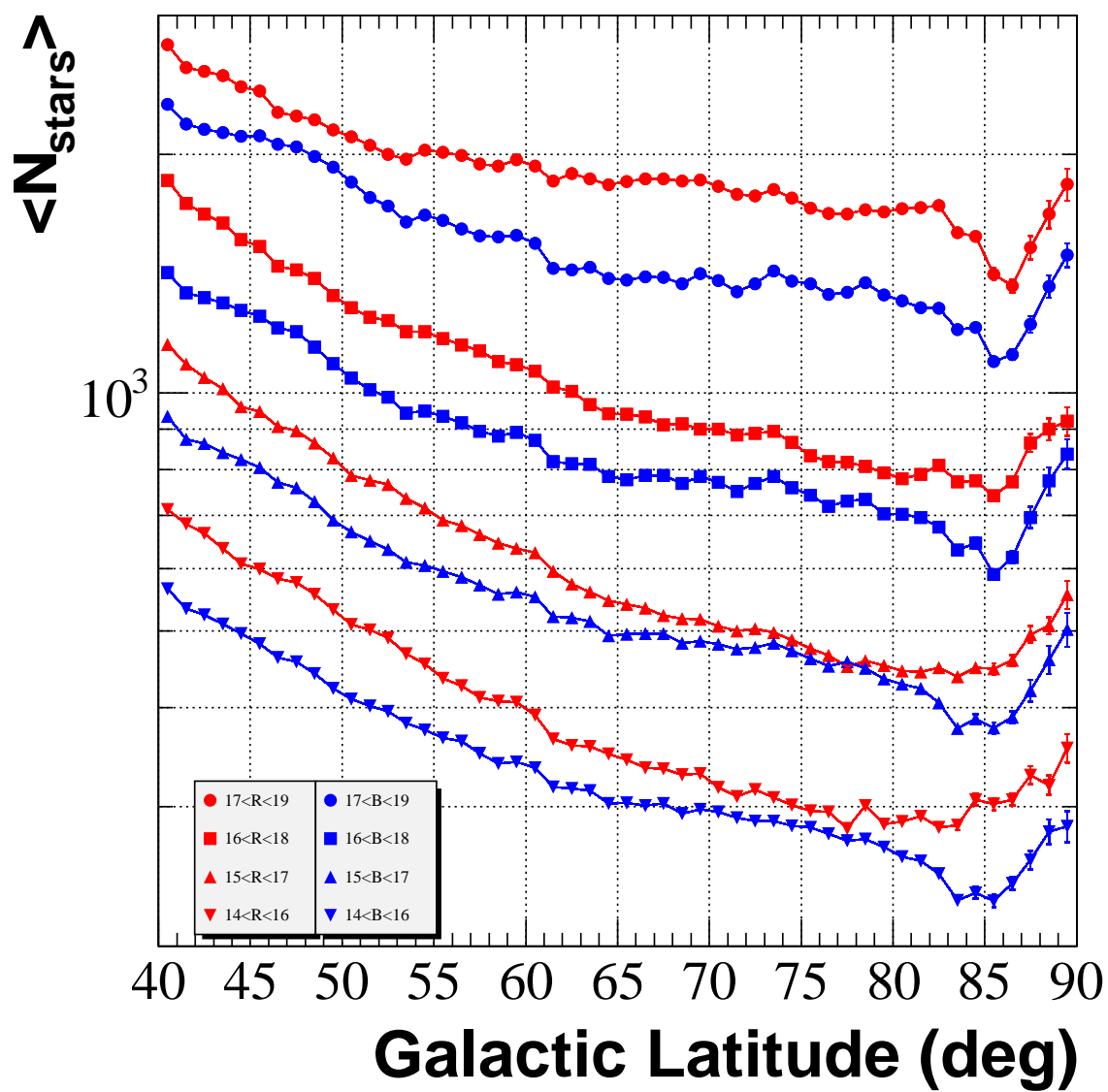
Figure 1. Number of stars per square degree N_{stars} versus galactic latitude for various R and B magnitude ranges.
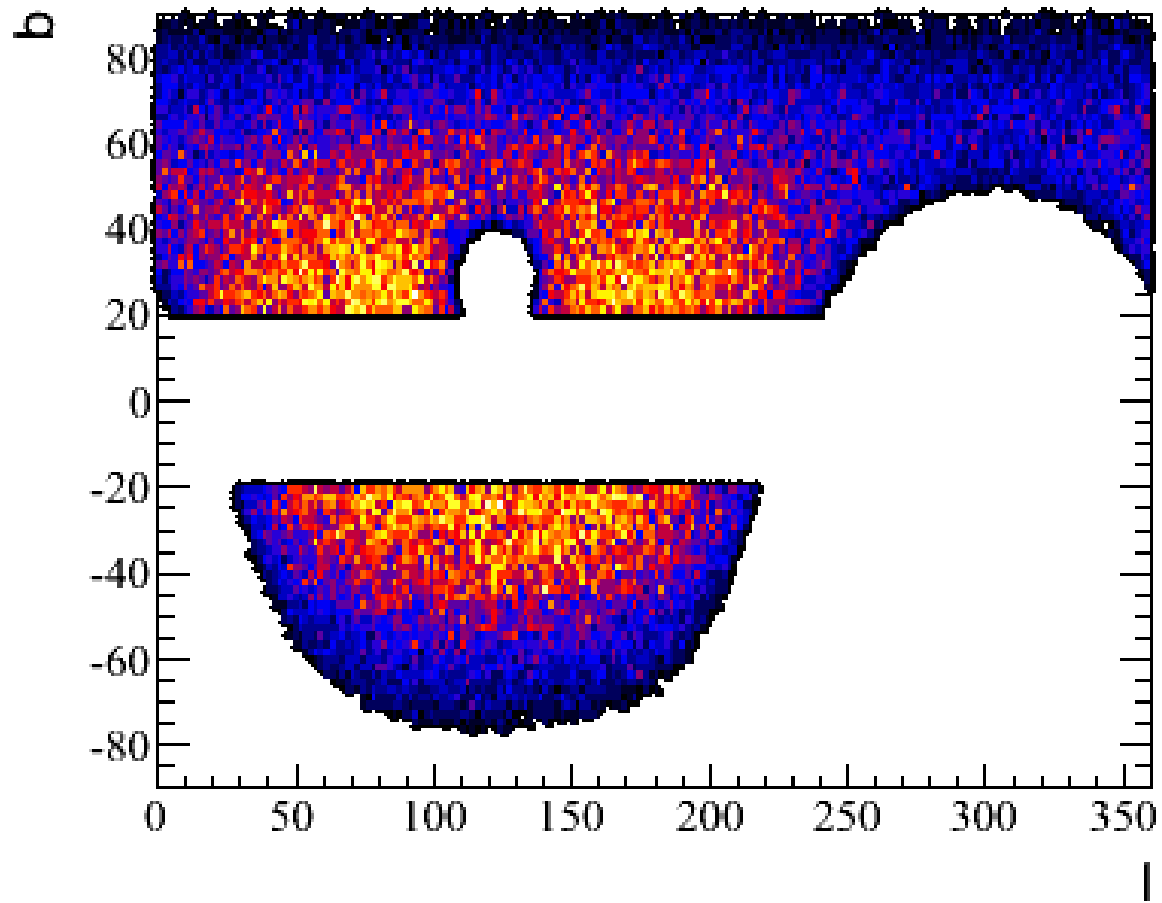
Figure 2. BigBOSS Footprint

Table 2. Number of Guide Stars

Galactic Latitude	N_{units}	$N_{sensors}$ per unit	% fields with 10 guide Stars	% fields with 1+ star each unit	%fields with both
$|b| \geq 20$	3	1	71	94	71
$|b| \geq 20$	3	2	98	99	97
$|b| \geq 20$	4	1	85	92	83
$|b| \geq 20$	4	2	99	99	99
$|b| \geq 70$	3	1	10	74	10
$|b| \geq 70$	3	2	82	97	81
$|b| \geq 70$	4	1	34	66	30
$|b| \geq 70$	4	2	98	96	95

4. GUIDE STAR SNR

The Mayall telescope ($D = 3.8\ m$) has an effective area of ($A_{effective} = 6.22\ m^2$) assuming 95% reflectance, 25% obscuration by the BigBOSS instrument and a corrector transmission of 77%. A star of magnitude (R) will provide a signal in number of electrons (N_{star}) of

$$N_{\text{star}} = 6.25 \times 10^{10-0.4R}\ \ [\text{photons}/m^2\ s\ \mu m]\ \times$$
$$T_{\text{atmosphere}}\ \ [\%] \times \text{QE}\ \ [e^-/\text{photon}]\ \times$$
$$A_{\text{effective}}\ \ [m^2] \times d\lambda_{\text{filter}}\ \ [\mu m]\ \times$$
$$T_{\text{filter}}\ \ [\%] \times t_{\text{exposure}}\ \ [s],$$

where $d\lambda_{filter}$ is the band pass width of the optical filter used and t_{exposure} is the exposure length. The noise from the signal is, of course,

$$\sigma_{\text{star}} = \sqrt{N_{\text{star}}}. \tag{1}$$

The number of background photons at Kitt Peak has been measured to vary between $20.9 \leq R_{\text{sky}} \leq 19.9$ at new and full moon respectively8. The sky signal per pixel (N_{sky}) is given by

$$N_{\text{sky}} = 6.25 \times 10^{(10\ -\ 0.4\ R_{\text{sky}})}\ [\text{photons}/m^2\ s\ \mu m\ \text{arcsecond}^2] \times$$
$$\text{QE}\ [e^-/\text{photon}] \times$$
$$A_{\text{effective}}\ [m^2] \times d\lambda_{\text{filter}}\ [\mu m] \times$$
$$T_{\text{filter}}\ [\%] \times t_{\text{exposure}}\ [s] \times$$
$$A_{\text{pixel}}\ [\text{arcsecond}^2] \tag{2}$$

. with an uncertainty of

$$\sigma_{\text{sky}} = \sqrt{N_{\text{sky}}}. \tag{3}$$

Similarily, the dark current per pixel (N_{dark}) and associated noise (σ_{dark}) are

$$N_{\text{dark}} = R_{\text{dark current}}\ [e^-/\text{pixel s}] \times t_{\text{exposure}}\ [s] \tag{4}$$
$$\sigma_{\text{dark}} = \sqrt{N_{\text{dark}}} \tag{5}$$

Finally, the read noise (σ_{read}) for the sensor, which is dependent on readout rate, is typically specified as an RMS value.

The signal to noise ratio for each guide star is given by

$$\text{SNR} = \frac{N_{\text{star}}}{\sqrt{\sigma_{\text{star}}^2 + \left(\sigma_{\text{sky}}^2 + \sigma_{\text{dark}}^2 + \sigma_{\text{read}}^2\right) \times N_{\text{pixel}}}}$$
$$= \frac{N_{\text{star}}}{\sqrt{N_{\text{star}} + (N_{\text{sky}} + N_{\text{dark}} + \sigma_{\text{read}}^2) \times N_{\text{pixel}}}} \tag{6}$$

The number of pixels used is typically the area where 50% of the energy is encircled (EE50). For example, with an (EE50) gaussian spot size of σ_{seeing}, the number of pixels used would be

$$N_{\text{pixels}} = \frac{A_{\text{seeing}}}{A_{\text{pixel}}}$$
$$= \frac{\pi \left(\frac{\sigma}{2}\right)^2}{A_{\text{pixel}}} \tag{7}$$

However, a Moffat profile is a better match to the seeing at Kitt Peak and would add around 20% to the number of pixels for EE50.

4.1 Guide Accuracy

The expected uncertainty of the centroid measurement is given by

$$\sigma_x = \frac{\sigma_{\text{seeing}}}{2.35 \times \text{SNR}} \tag{8}$$

$$\sigma_y = \frac{\sigma_{\text{seeing}}}{2.35 \times \text{SNR}} \tag{9}$$

by combining the measurement from 10 stars this uncertainty can be reduced by $\sqrt{10}$. The rms jitter (x and y) for 10 stars measured with SNR=10 with median seeing of 1.09"[9] is

$$\sigma_{x,y} = \frac{1.09"}{\sqrt{10} \times 2.35 \times 10} = 0.015 \text{ "} \tag{10}$$

5. GUIDE, FOCUS/ALIGNMENT UNIT

Based on the simulations summarized in Table 2 guide "units" consisting of two guide sensors and one intra and one extra-focal sensors are proposed. Using the e2v ccd230-42 as a baseline, Figure 5 shows the build up of a single guide, focus/alignment unit. Either three or four units will be mounted near the edge of the focal plate with either 90 or 120 degree spacing. Figure 5 shows a diagram of a four unit scheme.

6. SUMMARY

A guide, focus/alignment system hes been designed for the BigBOSS experiment. It will provide ten guide stars with signal to noise (SNR > 10) in over 97% of the survey. With ten guide stars, the system will provide a guide signal with precision of around 15 milli-arcseconds.

REFERENCES

[1] Schlegel, D. J., Bebek, C., Heetderks, H., Ho, S., Lampton, M., Levi, M., Mostek, N., Padmanabhan, N., Perlmutter, S., Roe, N., Sholl, M., Smoot, G., Martin White, A. D., Abraham, T., Jannuzi, B., Joyce, D., Liang, M., Merrill, M., Olsen, K., and Salim, S., "BigBOSS: The Ground-Based Stage IV Dark Energy Experiment," *Decadal Survey White Paper* - (2009).

[2] Roodman, A., "Focus and alignment of the dark energy camera using out-of-focus stars," *Proceedings of SPIE Volume* **8446**, 8446–254 (2012).

[3] Cavadore, C., "EOS 20D CMOS Detector Characterization." http://www.astrosurf.com/cavadore/technical-/detectors/EOS20D/index.html (2005).

[4] Simms, L. M., Figerb, D. F., Hanoldb, B. J., Kahn, S. M., and Gilmore, D. K., "Telescope Guiding with a HyVisi H2RG Used in Guide Mode," *Proc. SPIE* **7439**, 74390C–1 (2009).

[5] Vu, P., Fowler, B., Liu, C., Balicki, J., Mims, S., Do, H., and Laxson, D., "Design of Prototype Scientific CMOS Image Sensors," *Proc. SPIE* **7021**, 74390C–1 (2008).

[6] Bahcall and Soneira, "Comparisons of a standard galaxy model with stellar observations in five fields," *ApJS* **55**, 67 (1984).

[7] Simons, D., "Longitudinally averaged r-band field star counts across the entire sky," *Gemini Technical Note* **1**, 1–4 (1995).

[8] Massey, P., Armandroff, T., Veny, J. D., Claver, C., Harmer, C., Jacoby, G., Schoening, B., and Silva, D., "Direct imaging manual for kitt peak." http://www.noao.edu/kpno/manuals/dim/ (2002).

[9] Massey, P., Abraham, T., Bohannan, B., Claver, C., Glaspey, J., Green, R., and Wolff, R., "Seeing measurements," *NOAO Newsletter - Kitt Peak National Observatory* **59** (1999).
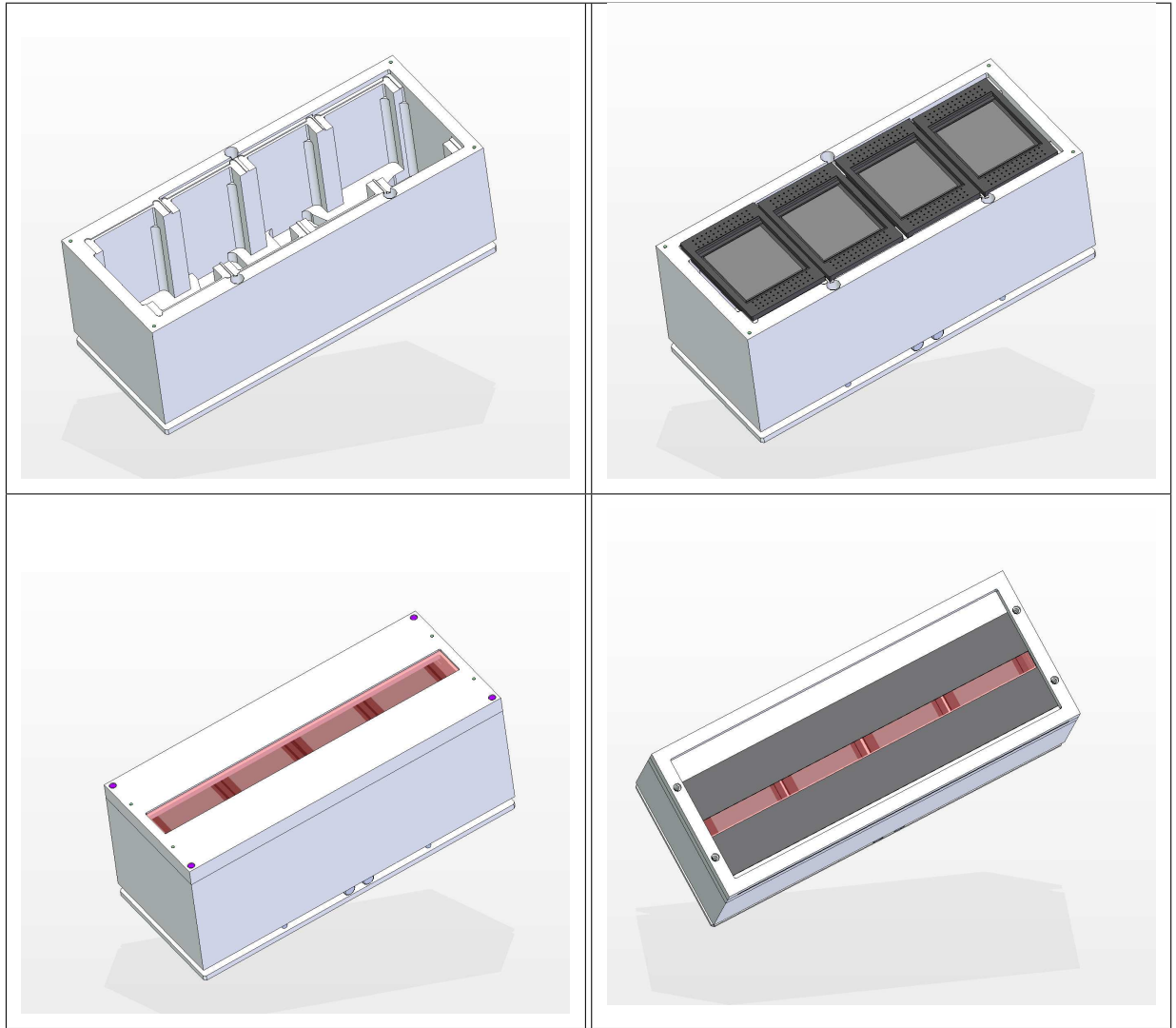
Figure 3. Build up of a guide, focus/alignment unit. Unit consists of 4 sensors, a narrow band R filter and a single blade Bonn Shutter. Readout electronics are located behind the sensors.
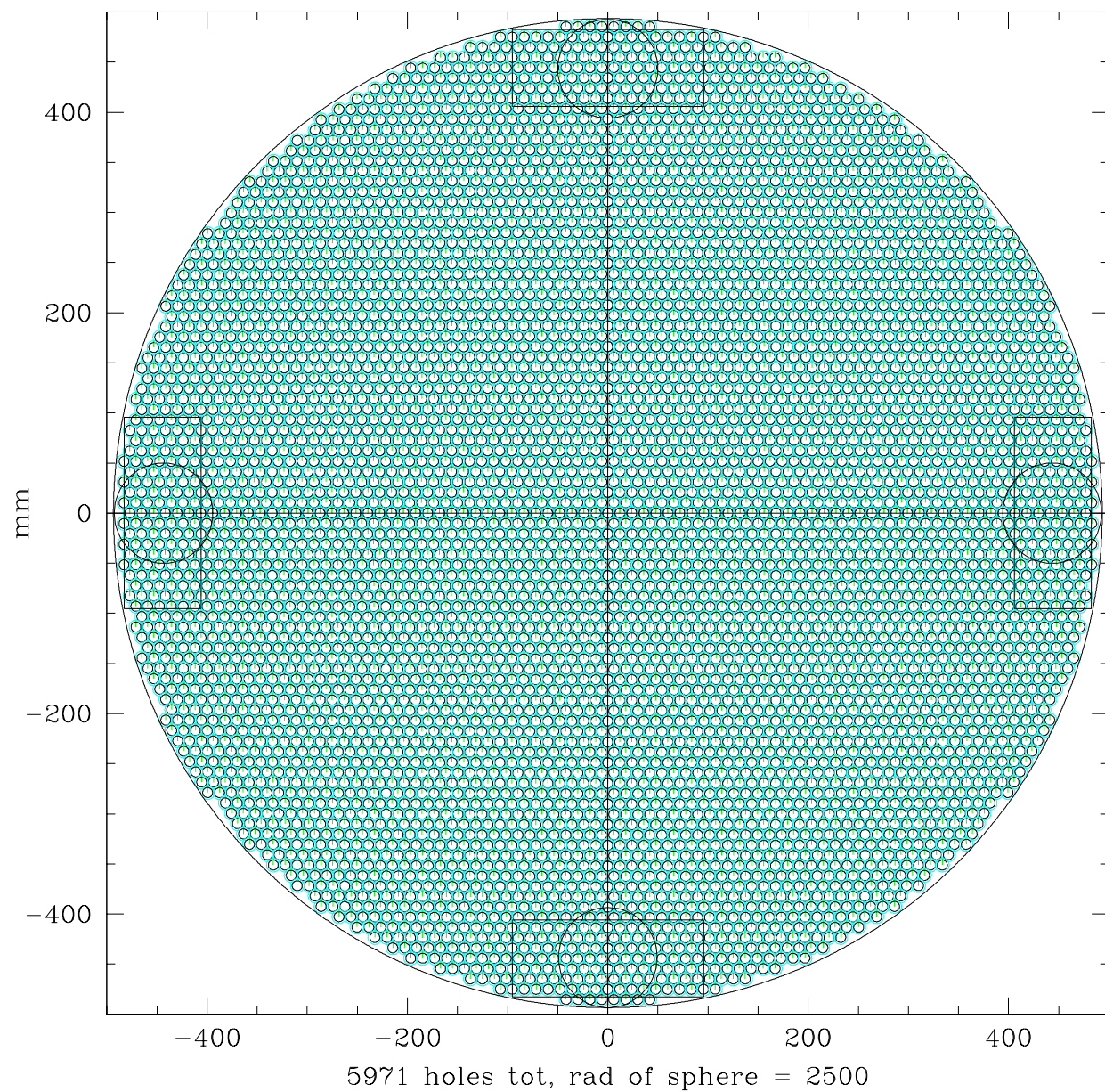
Figure 4. Location of the guide, focus and alignment units on the focal plate. Fiber actuator locations shown in cyan.